FRIB Preseparator Radiation Environment and Superconducting Magnet Lifetime Estimates

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Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

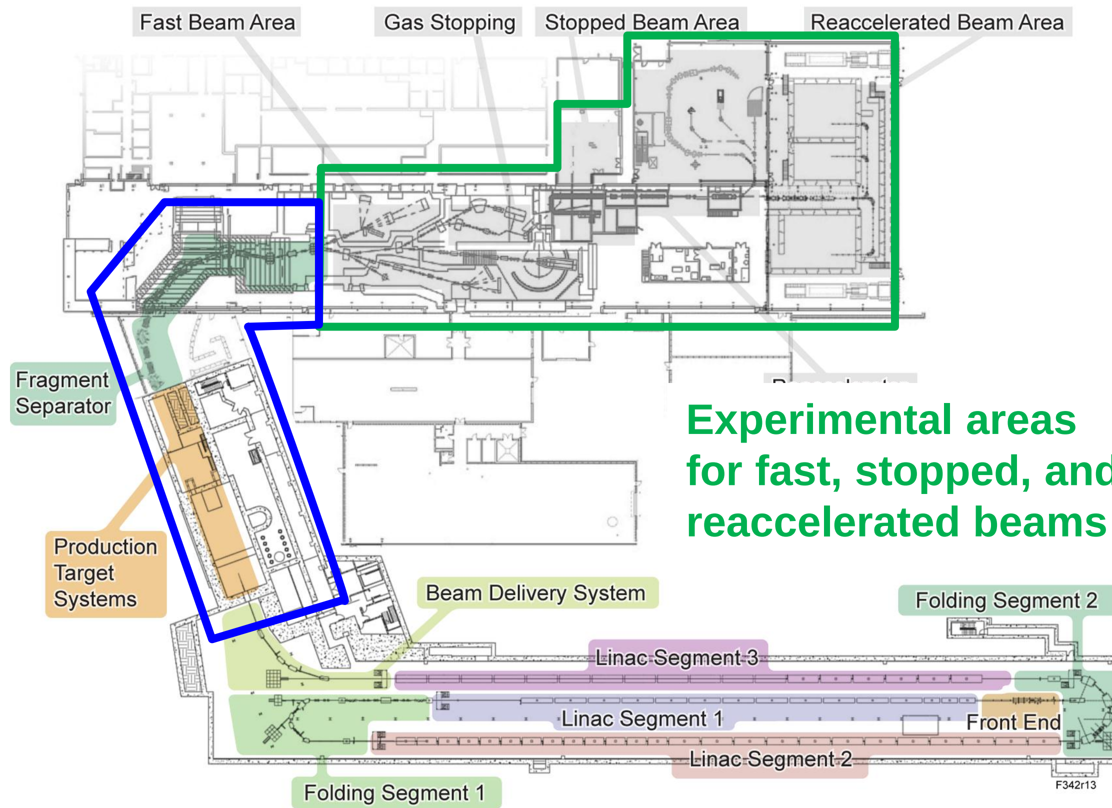
Outline

- FRIB, Preseparator Scope
- Radiation environment
- Expectations of magnet life from RIA R&D
- Magnet life from present study
  - Target + Primary Beam Dump
  - Target + Possible Second Beam Dump
- Summary and path forward

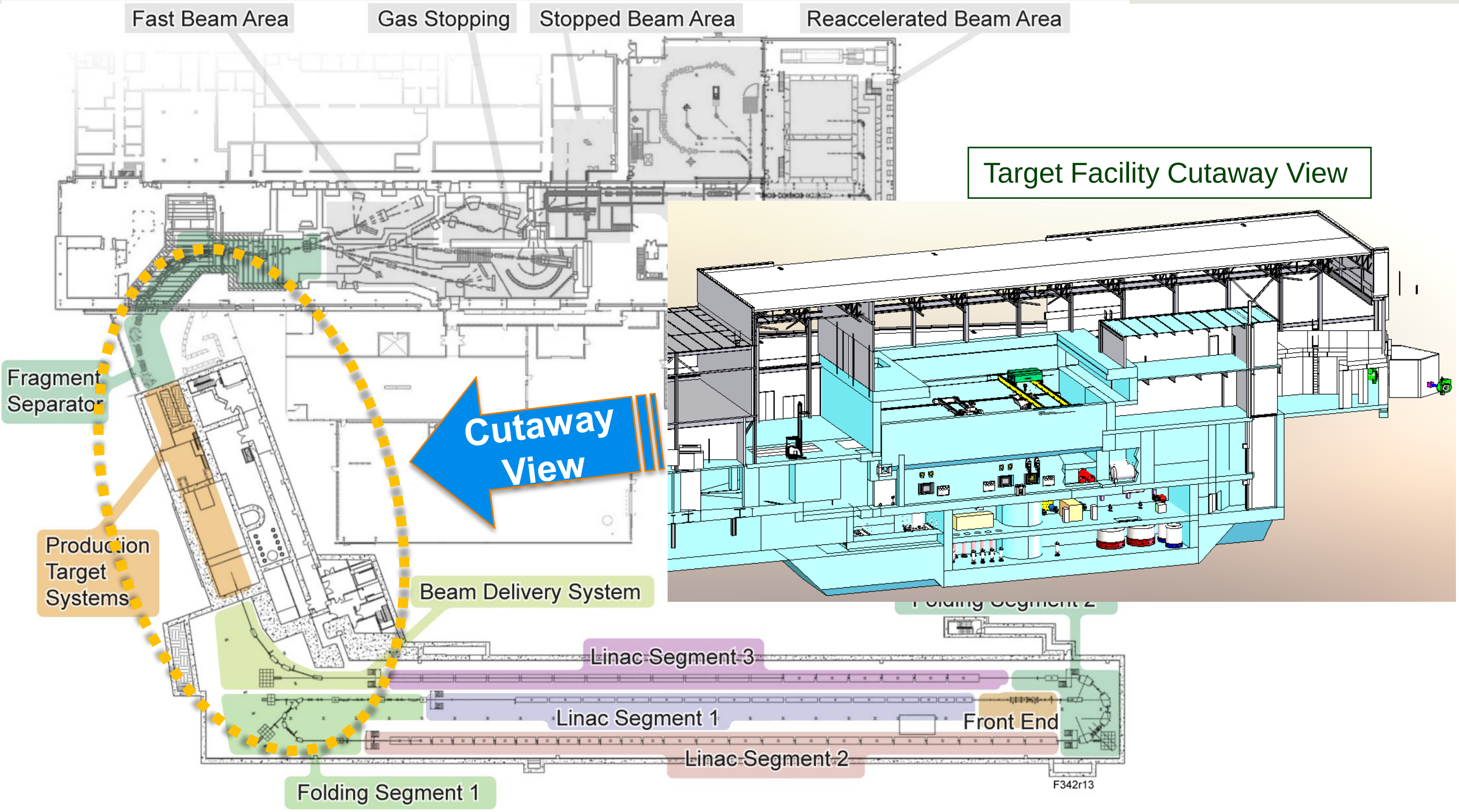
- Work supported by the U.S. Department of Energy Office of Science under Cooperate Agreement DE-SC0000661

FRIB Fragment Separator is within Experimental Systems Project Scope

- Facility requirements
  - Rare isotope production with primary beams up to 400 kW, 200 MeV/u uranium
  - Fast, stopped and reaccelerated beam capability
  - Experimental areas and scientific instrumentation for fast, stopped, and reaccelerated beams
- Experimental Systems project scope
  - Production target facility
  - Fragment separator

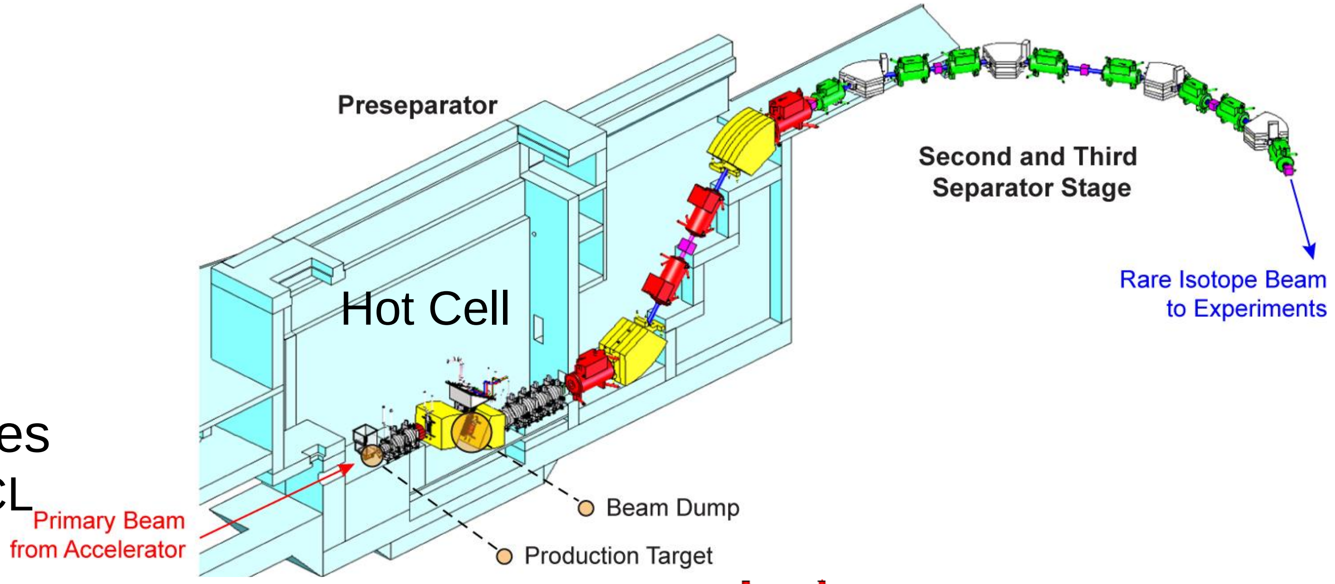


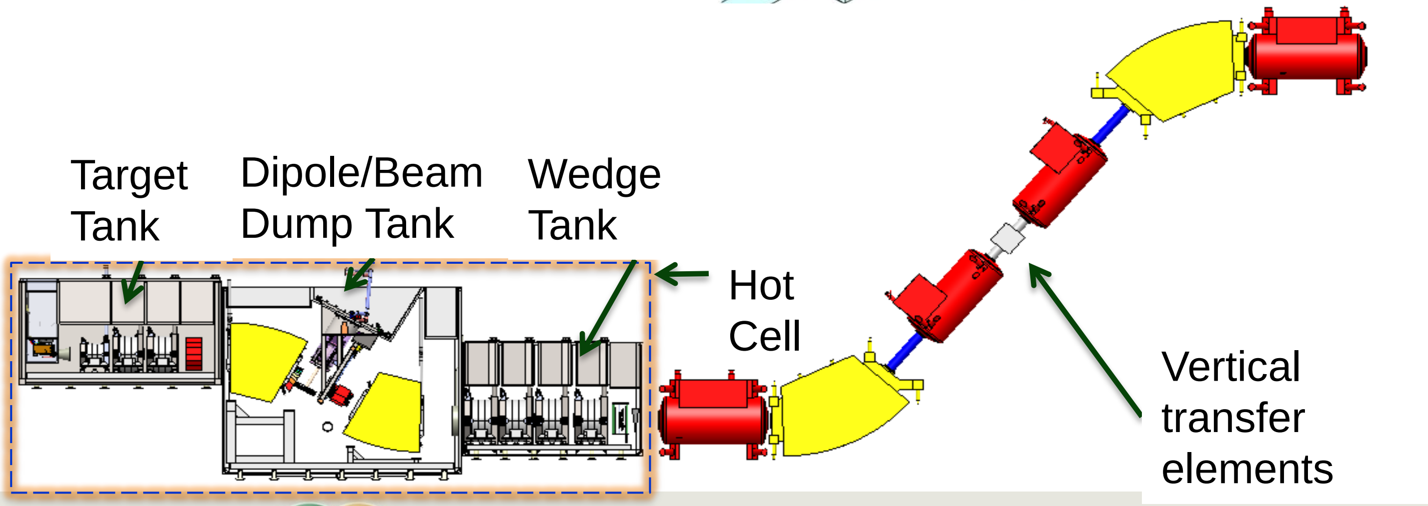
Fragment Preseparator Integrated With Target Facility



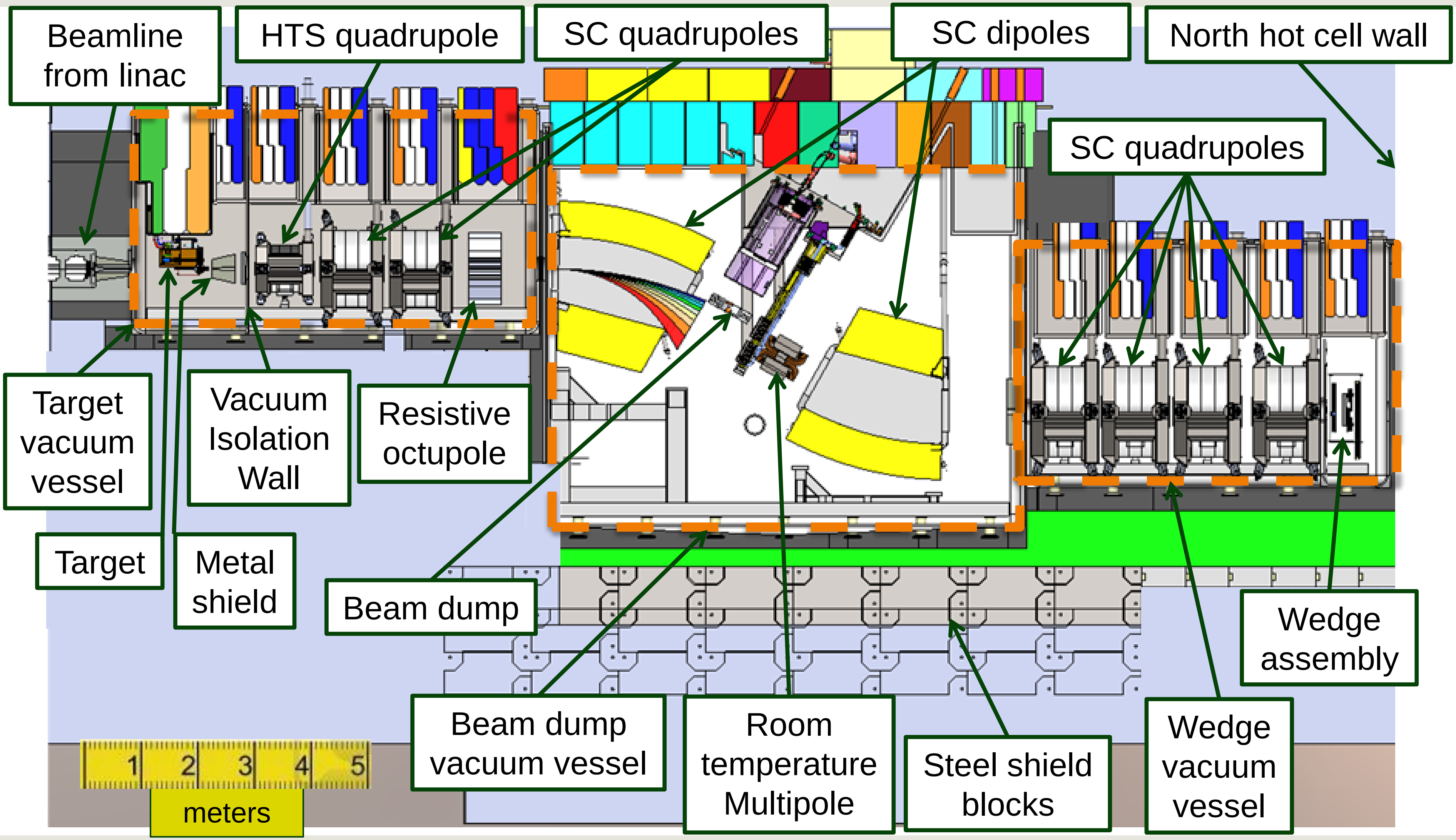
Fragment Separator Layout

- Preseparator
  - Horizontal Stage
    - » In “Hot Cell”
  - Vertical Stage
    - » Outside “Hot Cell”
- Separator
  - Second, Third Stages
    - » Within Current NSCL



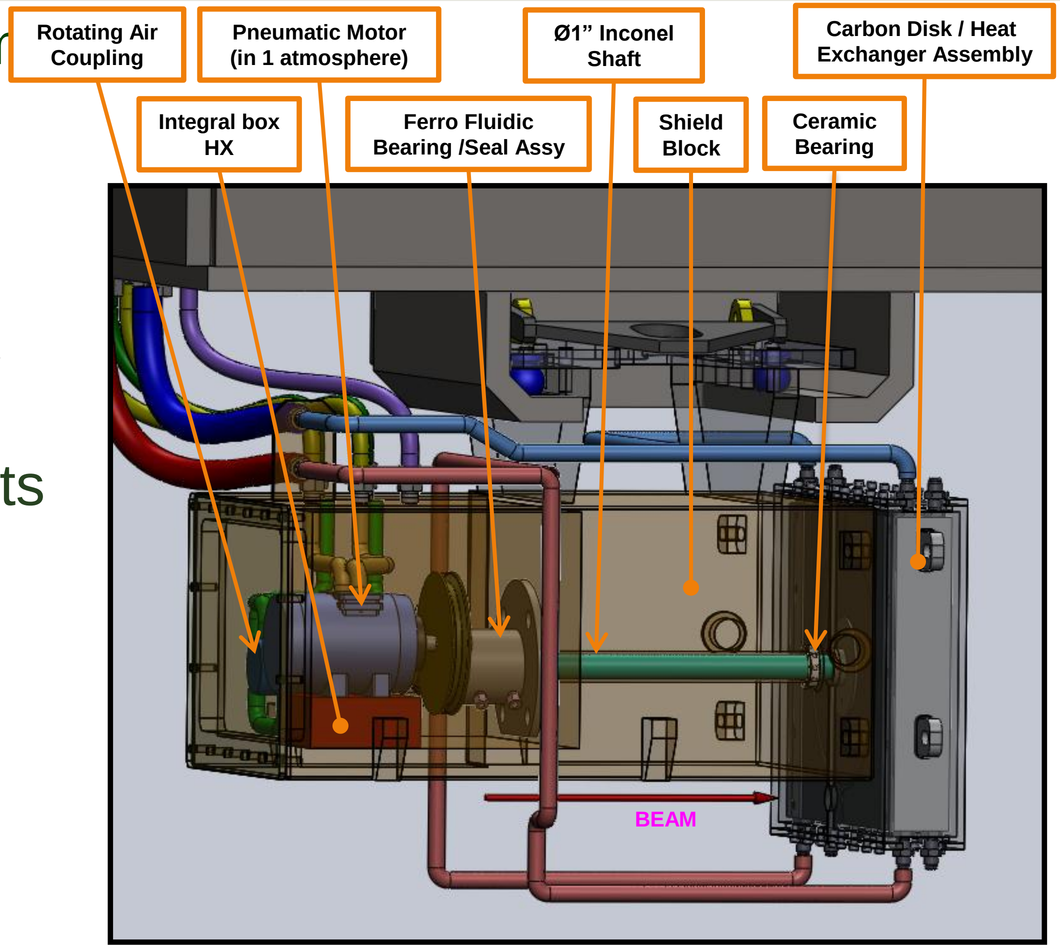


Preseparator and Vacuum Vessels in Hot Cell



Target Assembly Requirements

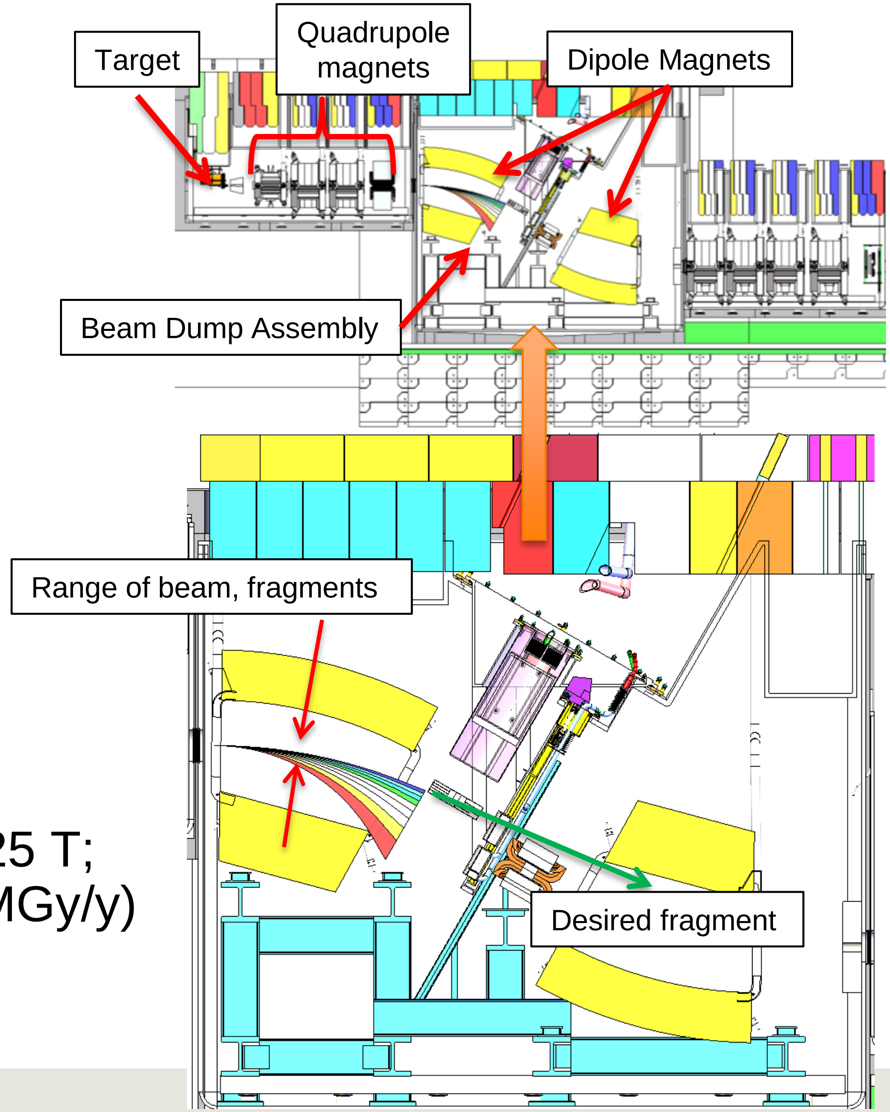
- 400 kW, 200 MeV/u ^{238}U beam
  - Up to 200 kW dissipated
  - 1 mm diameter
- Target speed requirement
  - 5,000 rpm disk rotation – needed to prevent overheating of carbon disks
- Water cooled HX, subject of ongoing design validation efforts
  - Allows rapid extraction of heat from beam interaction with target disks
- 1 mm positioning tolerance
- Remotely serviceable/ replaceable from lid
- Sufficient space available to accommodate future target designs (incl. liquid metal)



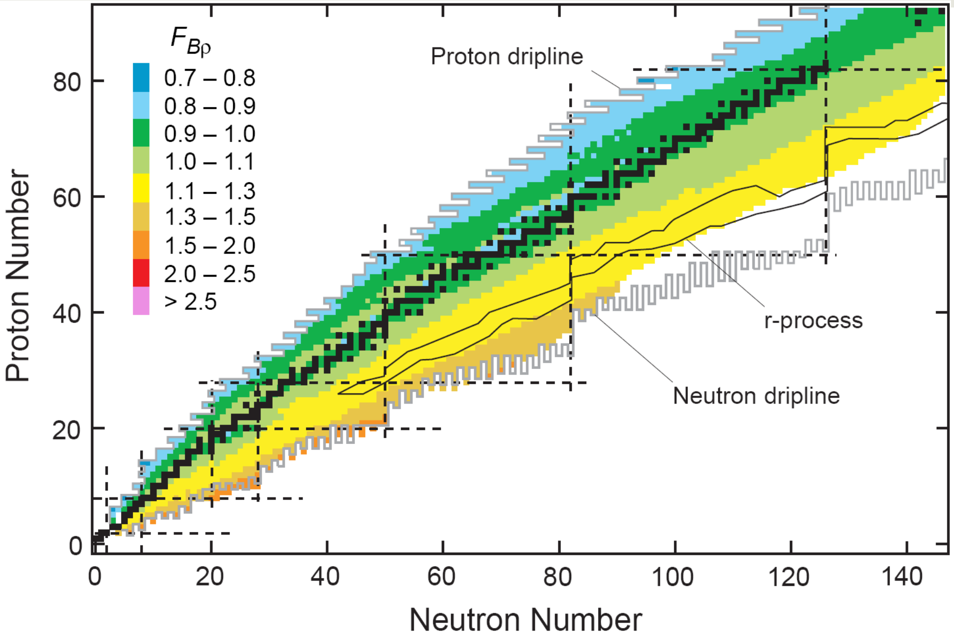
50 kW prototype target to verify design

Beam Dump Scope and Technical Requirements

- Intercept primary beam
  - Well-defined location
  - Needs to be adjustable
- High power capability up to 325 kW
  - High power density: ~ 10 MW/cm^3
- Efficient replacement
  - 1 year lifetime desirable
  - Remotely maintainable
  - Appropriately modular based on remote maintenance frequency
- Compatible with fragment separator
  - Must meet fit, form, function
- Compatible with operating environment
  - Vacuum ~10^{-5} Torr; magnetic field ~ 0.25 T; average radiation levels ~ 10^4 rad/h (1 MGy/y)
- Safe to operate

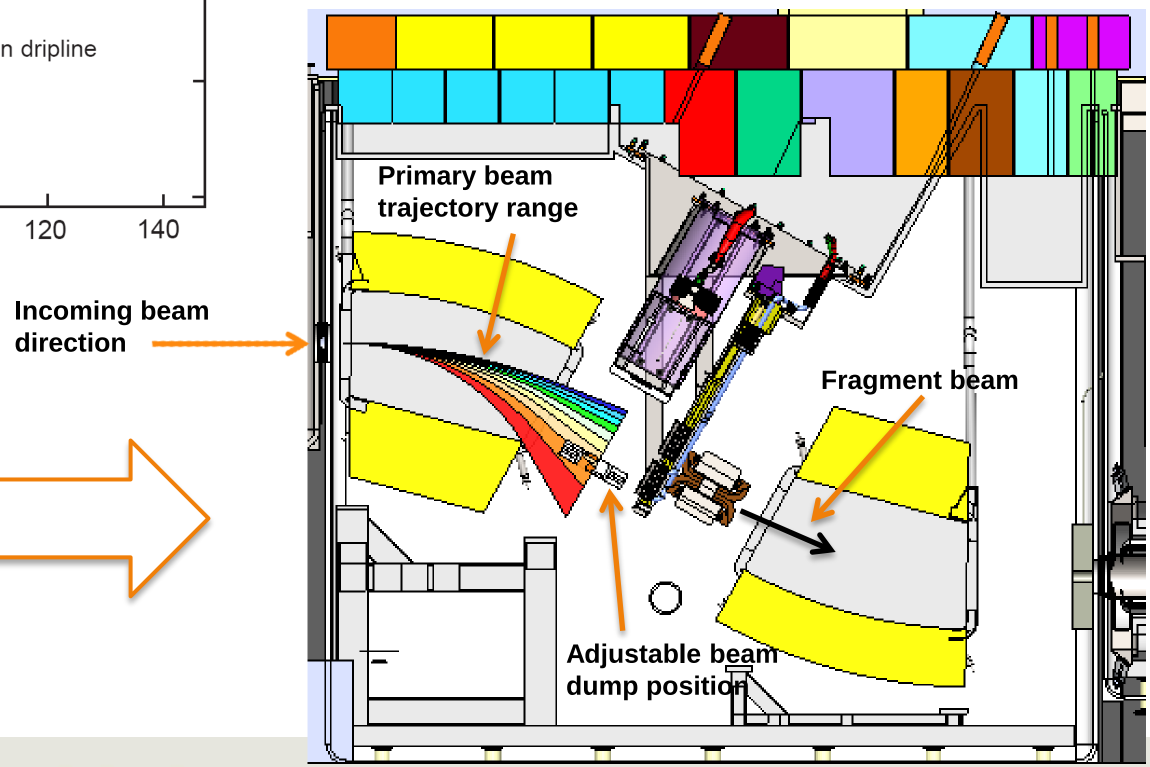


Primary Beam Position on Dump Changes with Fragment Selection



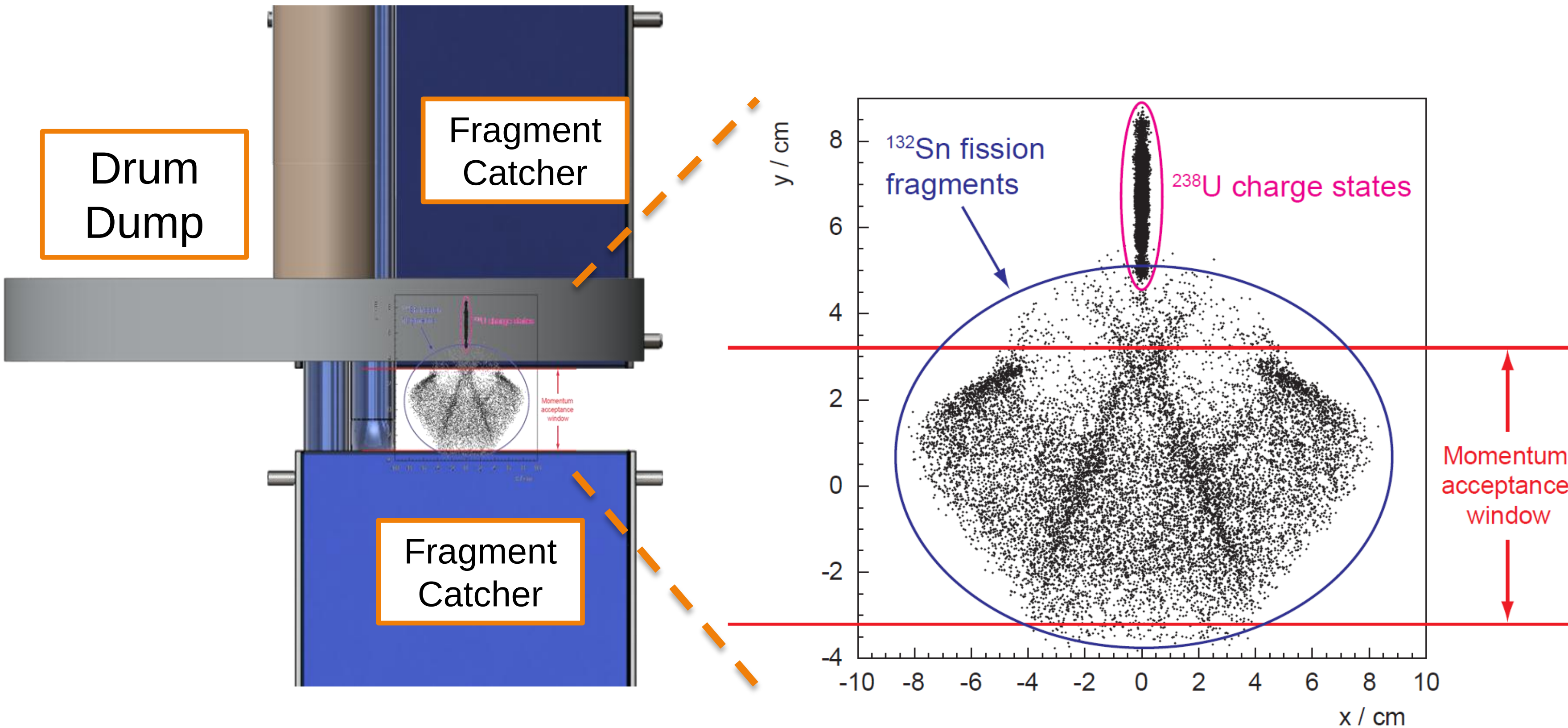
Color-code: $F_{B\rho}$ is the ratio of the magnetic rigidity of a given fragment to that of the primary beam.

The location of the primary beam at the beam dump is shown with the same color code.



Spatial Distribution of Beam and Fragments on Dump Depends on Fragment Selection

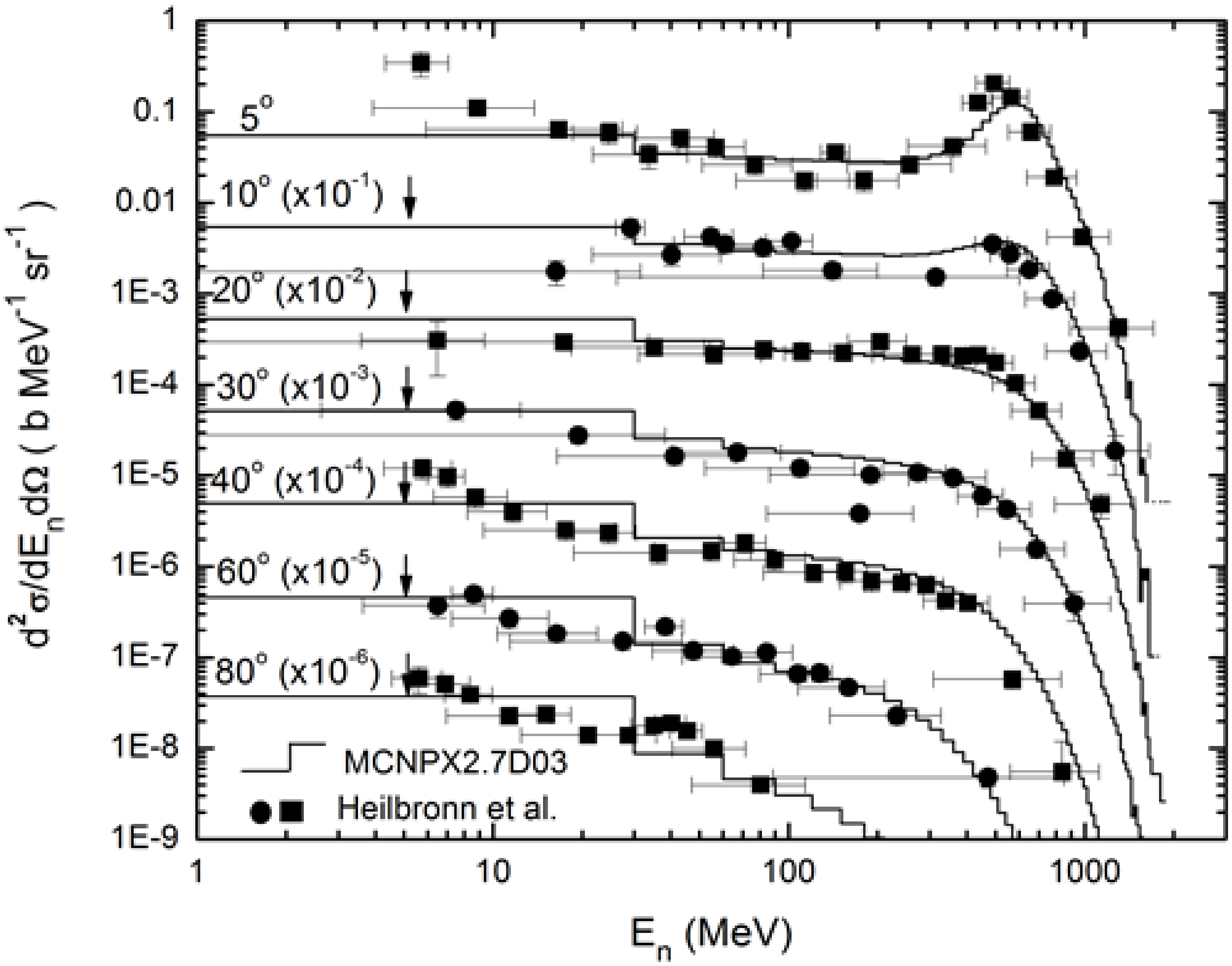
- Example: ^{132}Sn fragment distributions for ^{238}U + C fission
- Beam and fragments are in close proximity
  - 5 charge states, most restrictive “spot” sizes $\sigma_x \approx 2.3$ mm, $\sigma_y \approx 0.7$ mm
- Other beam/fragment combinations will be distributed differently



Neutron Production Cross Sections in Heavy Ion Reactions - Example

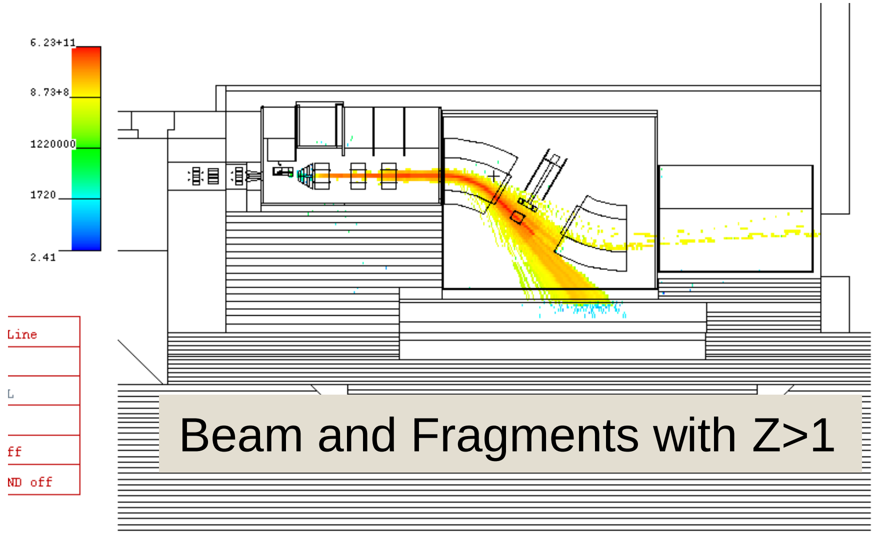
- 600 MeV/u Si + Cu

- HIMAC (NIRS, Chiba, Japan)
- L. Heilbronn, C. J. Zeitlin, Y. Iwata, T. Murakami, H. Iwase, T. Nakamura, T. Nunomiya, H. Sato, H. Yashima, R.M. Ronningen, and K. Ieki, "Secondary neutron-production cross sections from heavy-ion interactions between 230 and 600 MeV/nucleon", Nucl. Sci. and Eng., 157, pp. 142-158(2007)
- For thick-target yields, see:
  - T. Kurosawa et al., "Neutron yield from thick C, Al, Cu and Pb targets bombarded by 400 MeV/nucleon Ar, Fe, Xe, and 800 MeV/nucleon Si ions," Phys. Rev. C, 62, 044615 (2000)



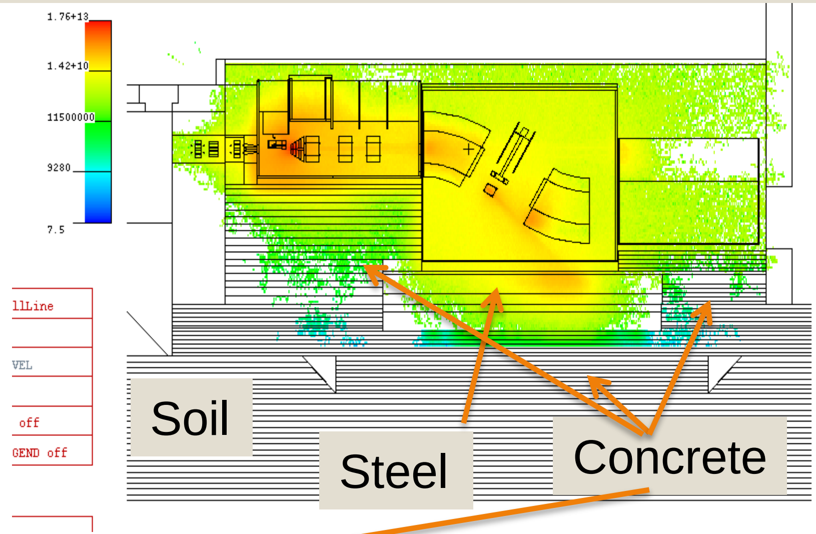
Study of Soil, Groundwater Activation

- 400 kW, 637 MeV/u ^{18}O

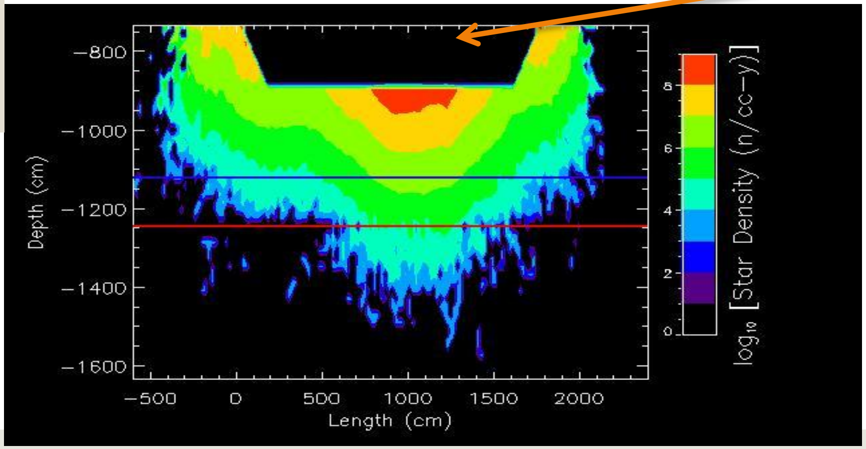


Beam and Fragments with Z>1

Neutron Flux Density (to 2×10^{13} n/cm^2-s)

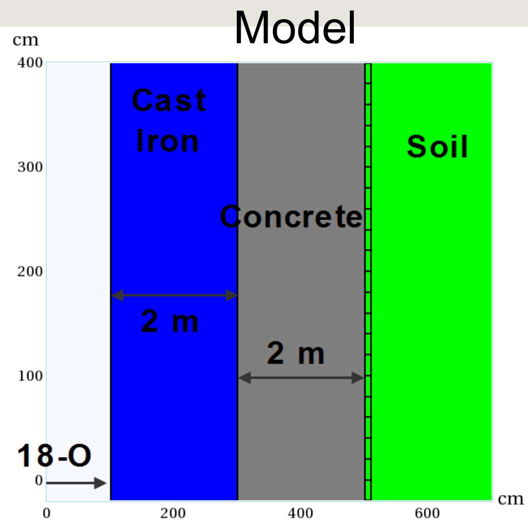


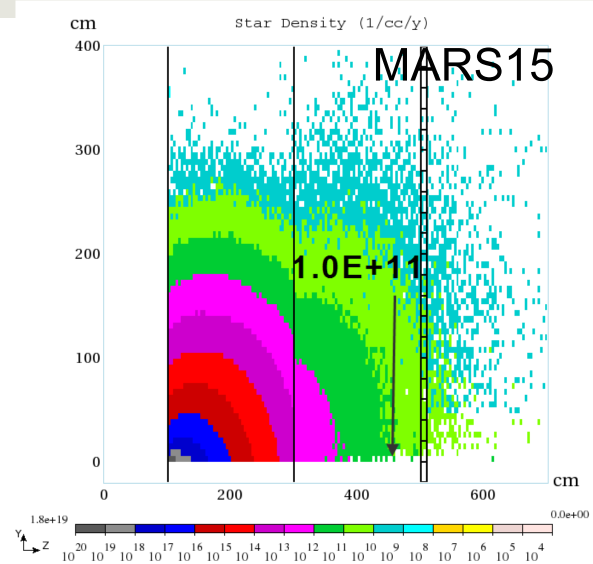
Star Density Production Rate in Soil

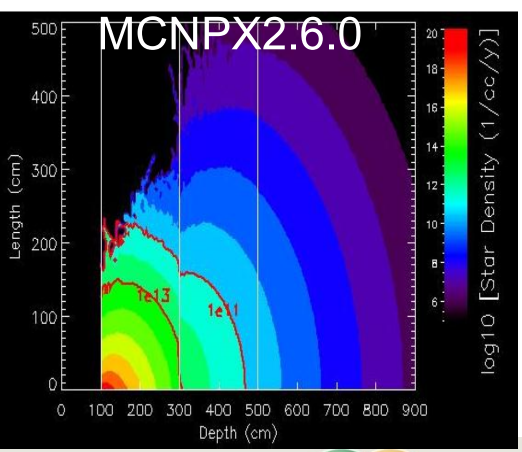


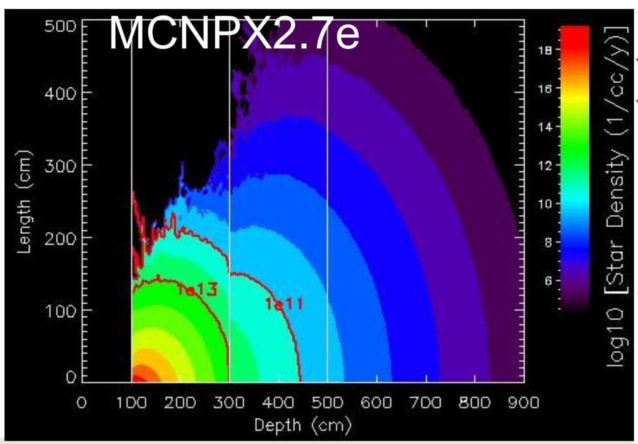
Codes are Benchmarked, Validated for Calculations Critical to Design

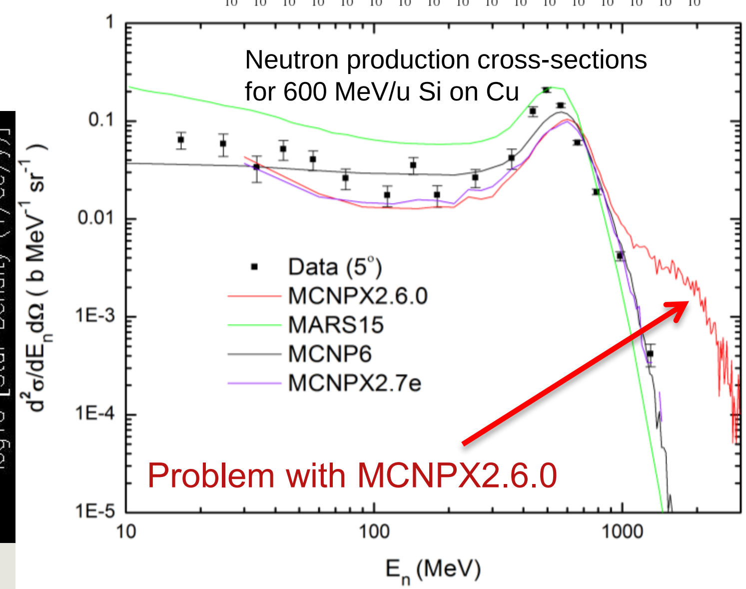
- Benchmark study performed for 400 kW 433 MeV/u ^{18}O beam
  - Upgrade energy
  - Energy of beam is at beam dump
- Purpose was to benchmark MCNPX (used for target building shield analysis) against MARS15 (used for linac shield analysis)
- Problem with MCNPX 2.6.0 – has not been used in analyses when transporting heavy ions - Stepan G. Mashnik, "Validation and Verification of MCNP6 Against Intermediate and High-Energy Experimental Data and Results by Other Codes, International Conference on Mathematics and Computational Methods Applied to Nuclear Science and Engineering (M&C 2011), Rio de Janeiro, RJ, Brazil, May 8-12, 2011.



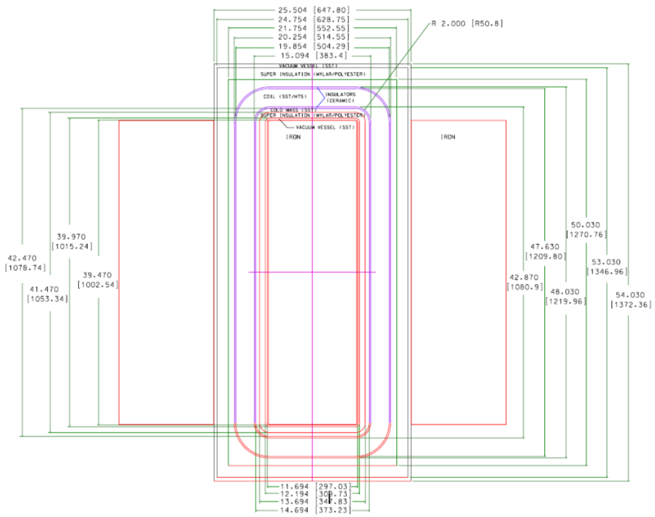


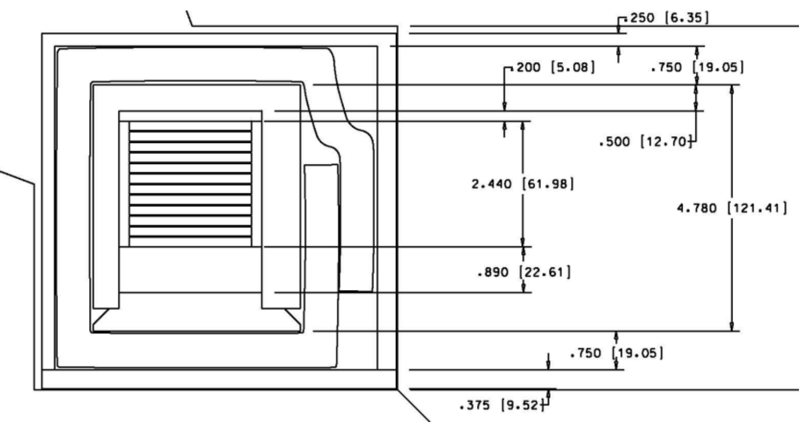


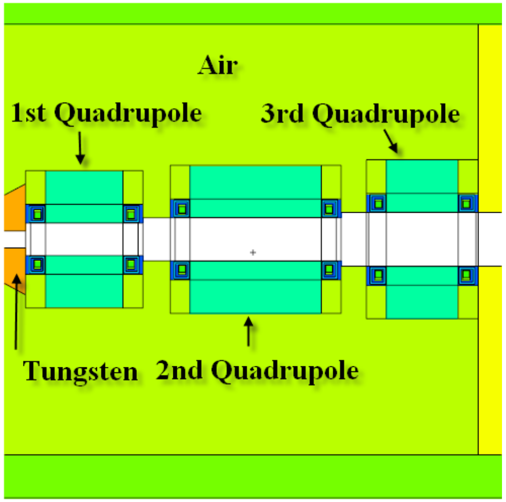


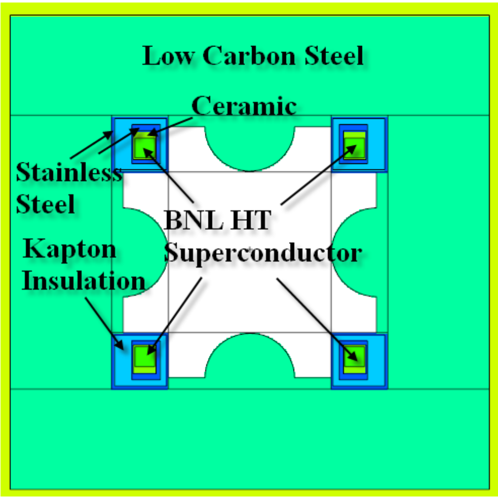


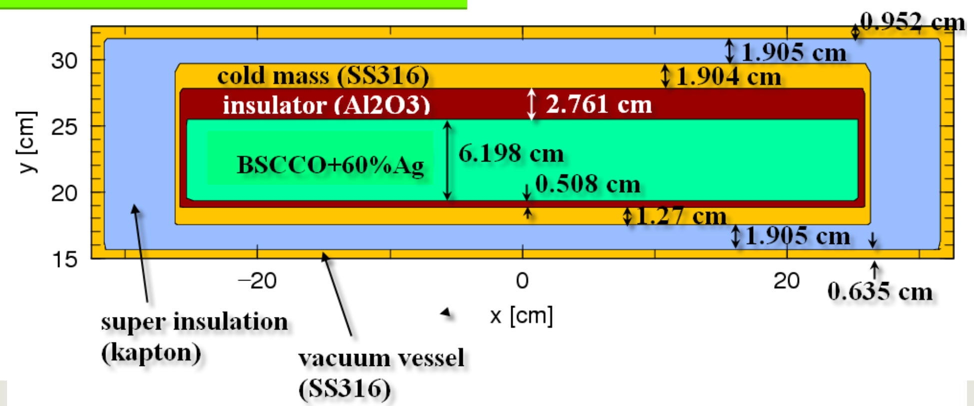
RIA R&D Work: Model of BNL Magnet Design circa 2006





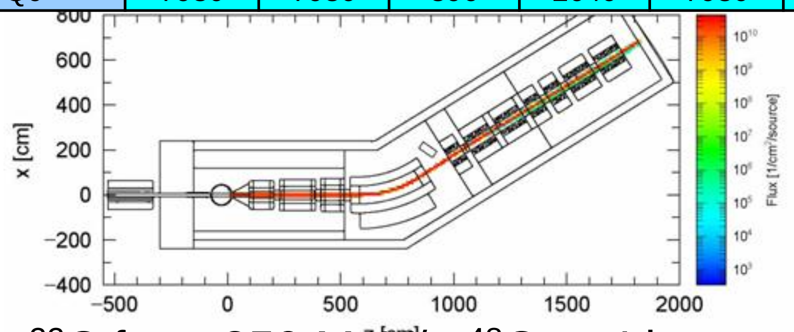


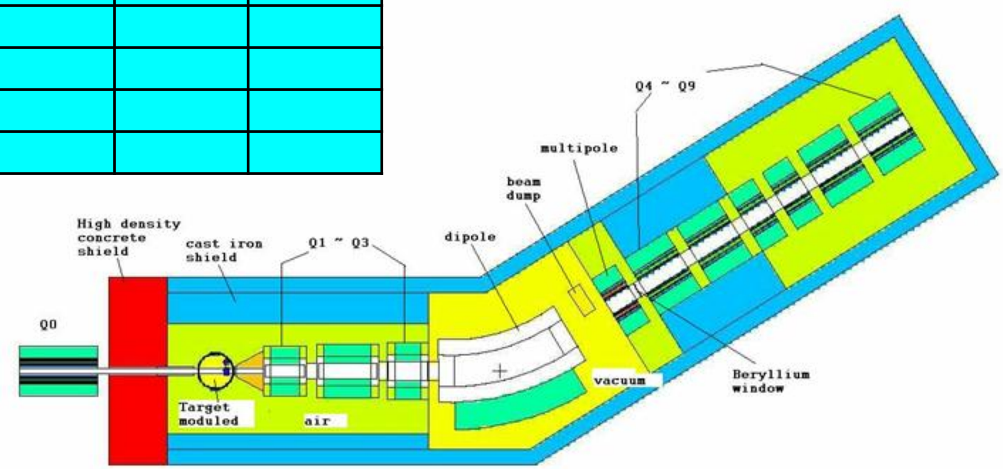




RIA R&D Expectations: Coil Life [y]

Target	Liquid lithium target					Beryllium target		
Projectiles	^{48}Ca	^{48}Ca	^{86}Kr	^{136}Xe	^{238}U	^{48}Ca	^{86}Kr	^{136}Xe
Energy (MeV/nucleon)	350	500	520	500	400	500	520	500
Q1	9	5	7	13	33	8	17	29
Q2	14	3	21	57	132	33	66	113
Q3	25	8	47	88	198	53	198	264
Dipole	12	5	20	20	396		264	396
Sextupole	26	23	19	61	38			
Q4	396	113	79	396	198			
Q5	1980	159	264	793	793			
Q6	7930	793	396	3960	3960			
Q7	7930	793	793	7930	7930			
Q8	39600	2640	1980	7930	7930			
Q9	7930	7930	396	2640	7930			





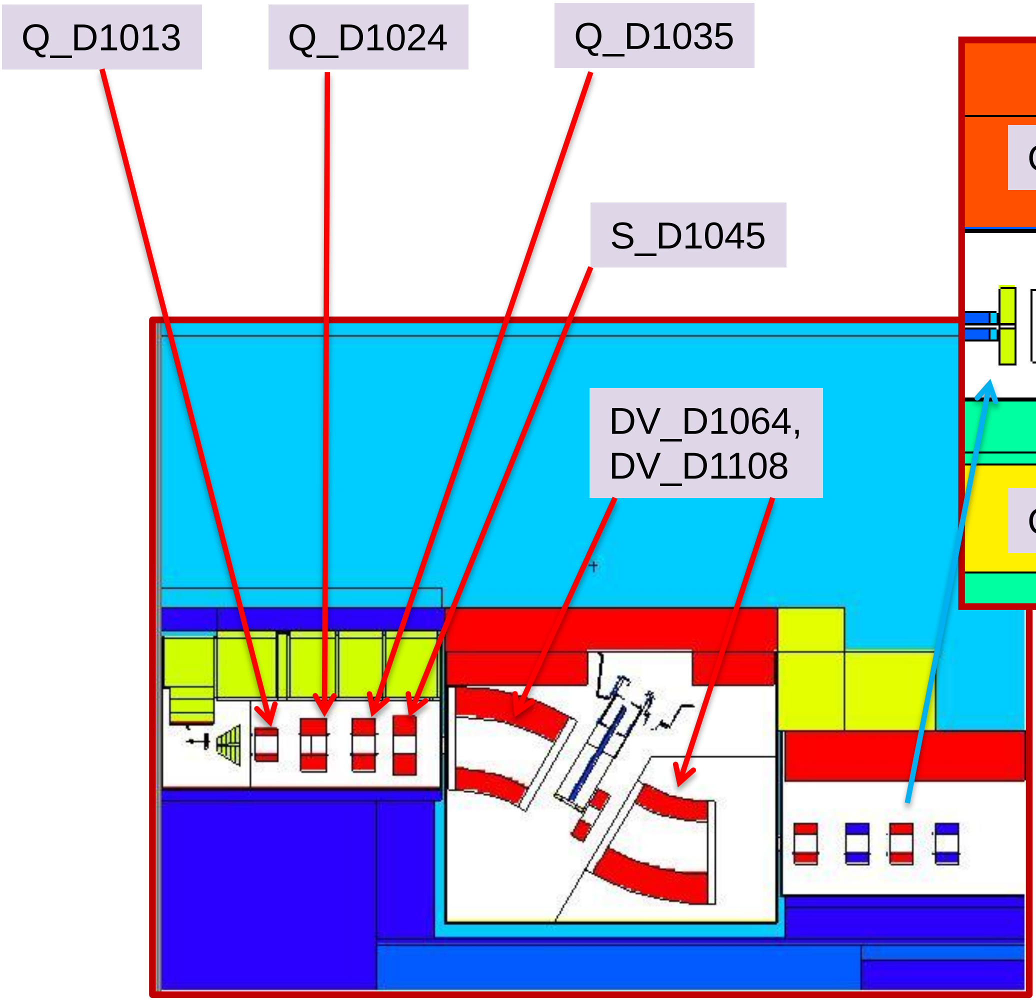
^{22}C from 350 MeV/u ^{48}Ca + Li

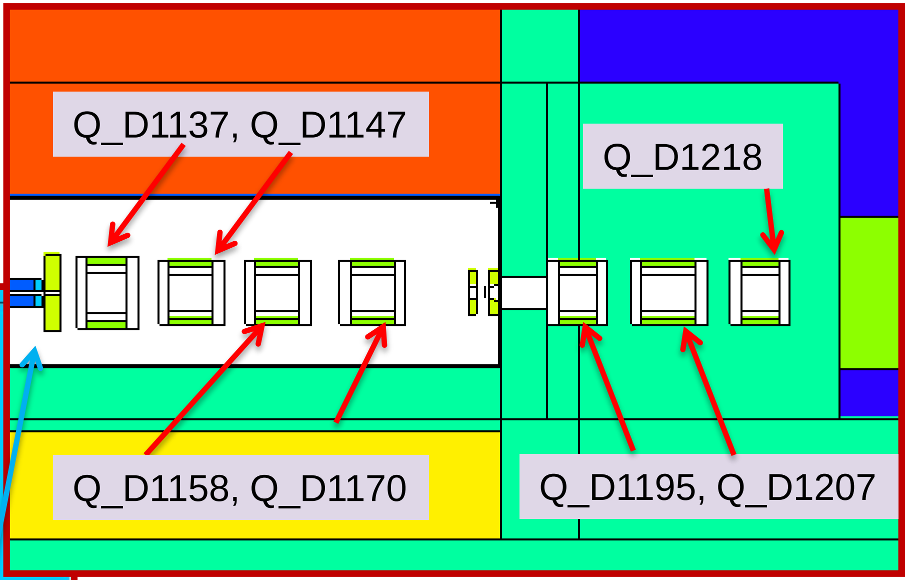
FRIB Baseline Beam Parameters

- Beam Parameters
  - 400 kW on target
  - Target extent is 30% of ion range
- Baseline Energies
  - Upgrade energies ~x2 larger
    - » Secondary fluxes ~ x4 larger
  - Beam current (for 400 kW) ~ x0.5 – smaller
    - » Expect doses to increase by ~x2
    - » Angular distributions more forward peaked
- Operational Year
  - 2×10^7s (5556 h)

Beam Ion	Specific Energy [MeV/u]	Particle Current for 400 kW [ions/s] [$\times 10^{13}$]	Target Thickness for ~ 30% of Ion Range [cm]
^{18}O	266	52	2.22
^{48}Ca	239.5	22	0.79
^{86}Kr	233	12	0.43
^{136}Xe	222	8	0.29
^{238}U	203	5	0.17

Radiation Heating in Magnets Determined
Supports Magnet and Non-conventional Utility Design





Two models were used for MCNP6, PHITS calculations of heating in magnets: the large-scale model (left) and a model for the possible second beam dump implementation (above)

Magnet Technologies Assumed

- Magnet Technologies Assumed

Order in Separator	FRIB ID	Magnet Type	Coil Technology
1	Q1b	Quadrupole	Cu+Stycast
2	Q2b	Quadrupole	Not yet modeled
3	Q3b	Quadrupole	Cu+Stycast
4	Q_D1013	Quadrupole	HTSC (YBCO)
5	Q_D1024	Quadrupole	NbTi+Cu+Cyanate Ester
6	Q_D1035	Quadrupole	NbTi+Cu+Cyanate Ester
7	OCT_D1045	Octupole-Sextupole	Hollow Tube Cu+MgO
8	DV_1064	Dipole	NbTi+Cu+Cyanate Ester
9	S_D1092	Octupole-Sextupole	Hollow Tube Cu+MgO
10	DV_D1108	Dipole	NbTi+Cu+Cyanate Ester
11	Q_D1137	Quadrupole	NbTi+Cu+Cyanate Ester
12	Q_D1147	Quadrupole	NbTi+Cu+Cyanate Ester
13	Q_D1158	Quadrupole	NbTi+Cu+Cyanate Ester
14	Q_D1170	Quadrupole	NbTi+Cu+Cyanate Ester

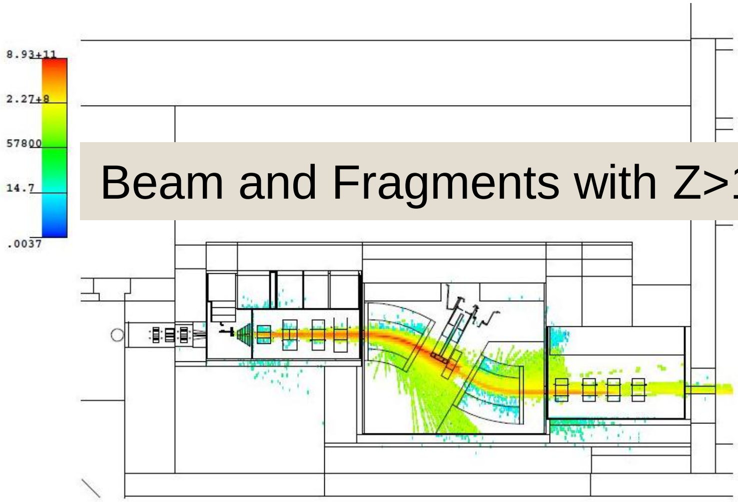
- Expected Lifetime in Units of Radiation Dose [Gy]

Material	Expected Lifetime [Gy]
HTSC	$(1 – 2)x10^8$
NbTi	$\sim 5x10^8$
Nb_3Sn	$\geq 5x10^8$
Copper	$> 10^8$
Ceramics(Al_2O_3, MgO, etc)	$> 10^9$
Organics	$> 10^6$ to 10^8

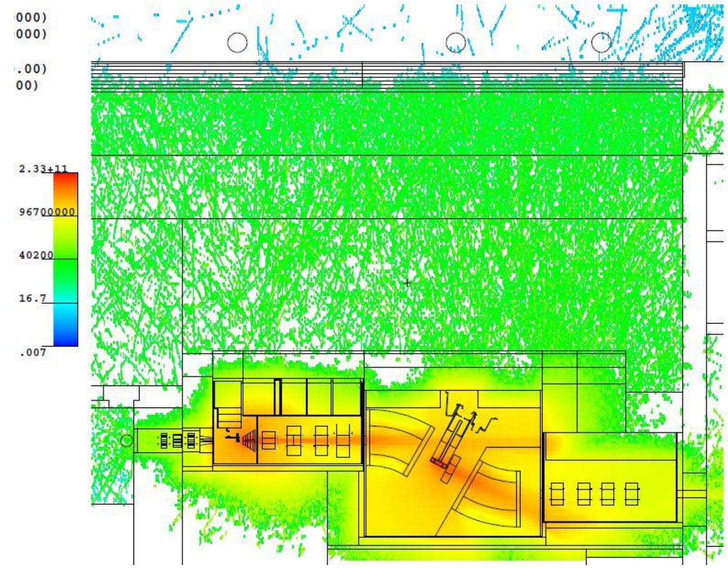
Prompt Radiation Maps

- 400 kW, 550 MeV/u ^{48}Ca

Neutron Flux Density (to $2x10^{11}$ n/cm^2-s)

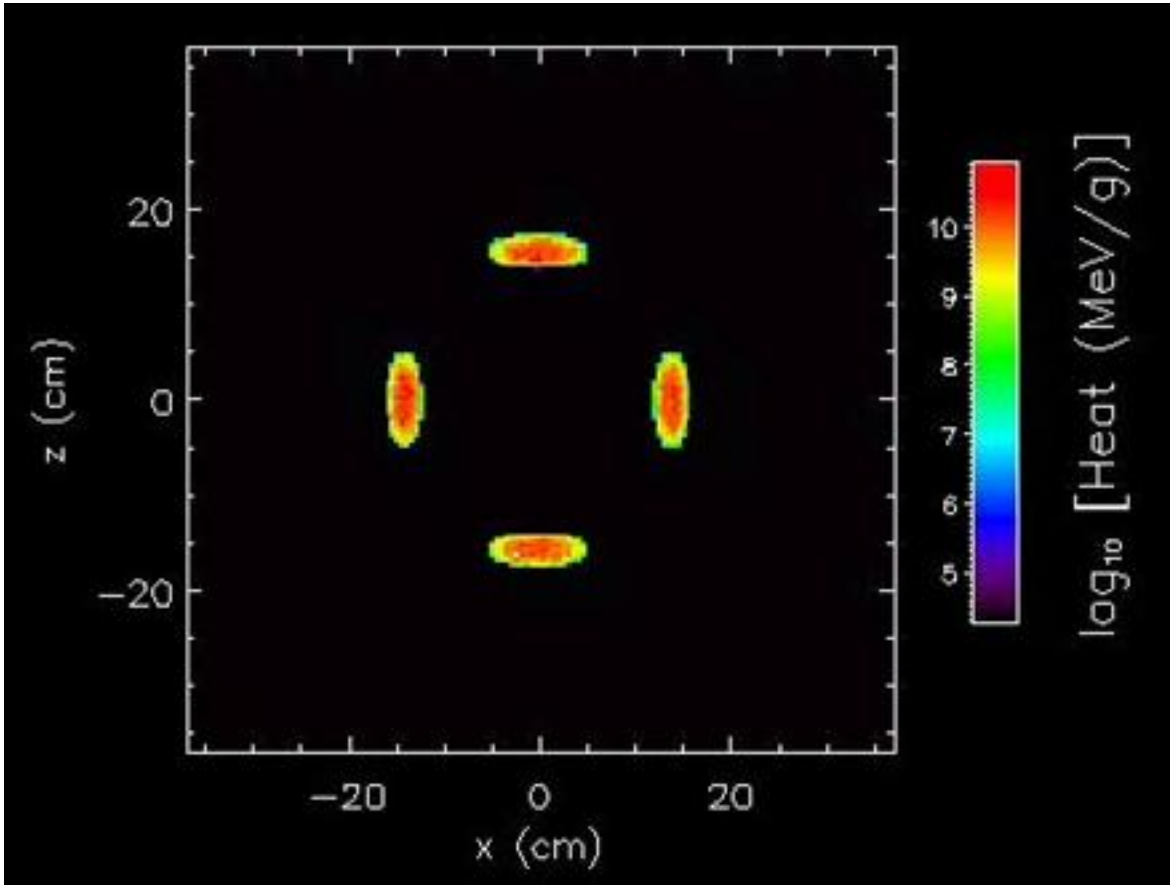


Beam and Fragments with Z>1



Preseparator tuned for ^{42}P

Radiation Heating in Magnets
Example: Heating, Quadrupole Cross-section



2D IDL frames of MCNP6 heating mesh tally into Windows Movie Maker

$\Delta x = \Delta z = 1$ cm; $\Delta y = 0.5$ cm

Expected Life of Preseparator Magnets

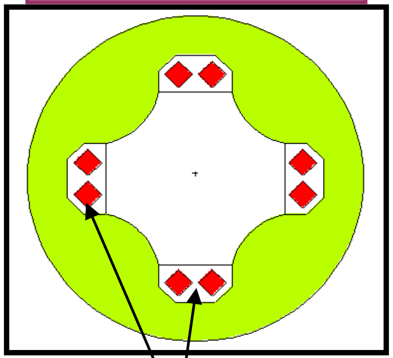
- Iron, W shields studied
  - Need to value-engineer shield
  - Average heating quoted, maximum values under study and are likely factors of several larger

	Iron Shield					W Shield				
Projectiles	O18	Ca48	Kr86	Xe136	U238	O18	Ca48	Kr86	Xe136	U238
Energy (Mev/nucleon)	266	239.5	233	222	203	266	239.5	233	222	203
	Expected Life [y]					Expected Life [y]				
Q1b (BDS)	1.7E+04	3.3E+04	6.3E+04	6.9E+04	9.0E+04		1.63E+04	2.72E+04	4.55E+04	4.55E+04
Q2b (BDS)										
Q3b (BDS)	3448	6784	11765	14493	19011		3401	5675	9452	5675
Q_D1013	2	4	5	68	6		9	15	32	6
Q_D1024	149	368	391	481	435		397	1323	2415	2778
Q_D1035	66	80	130	495	179		242	180	120	17
OCT_D1045	1818	1946	7364	495	4630		7003	11820	16077	14205
DV_1064	37	28	45	561	36		28	42	96	35
S_D1092	71	79	5	78	5		80	7	391	5
DV_D1108	3333	3731	706	867	2688		284	370	318	407
Q_D1137	2500	13228	994	2907	3067		2463	26178	25126	8532
Q_D1147	1333	2404	216	39	6570		16722	16835	3086	1381
Q_D1158	1333	7062	7645	72	21930		92593	6196	30	329
Q_D1170	1048	30303	862	110	21645		45045	5675	12690	2841

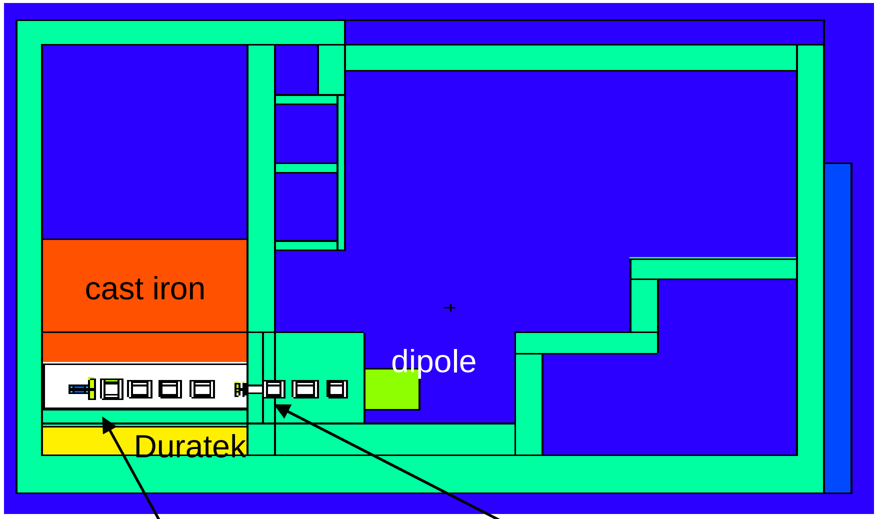
Model of Geometry for PHITS Calculation

4 quads before the wall (Q1 to Q4), in Al tank.
3 quads after the wall (Q5 to Q7), in concrete.
Bore diameters: Q1 – 44 cm, others – 40 cm.
Lengths with coils [cm]: 79,84,84,84,76,96,76

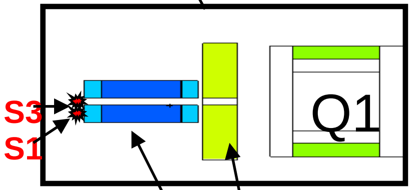
quadrupole,
transverse view



Coils (NbTi+Cu+
Stycast or Cyanate Ester)



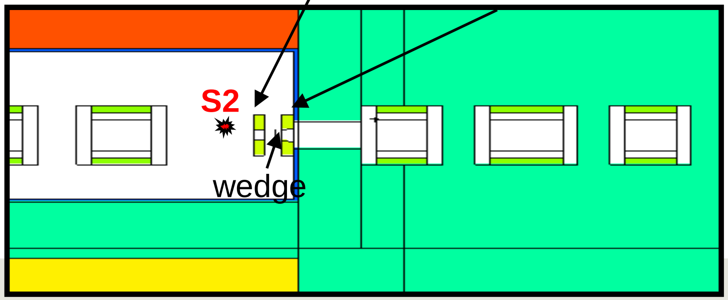
86Kr beams, E = 233 MeV/u
S1,S2,S3: 300,10,0.32 kW



beam dump
(water, aluminum)

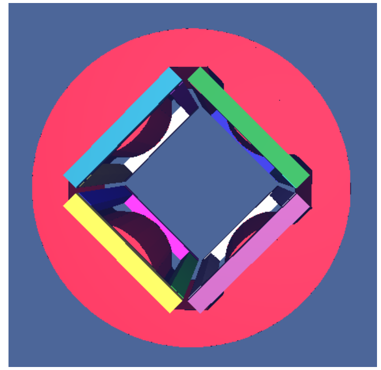
collimator (Hevimet)

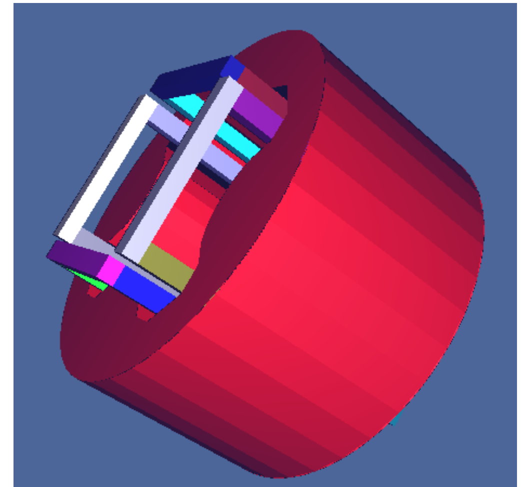
aperture, collimator (Hevimet)

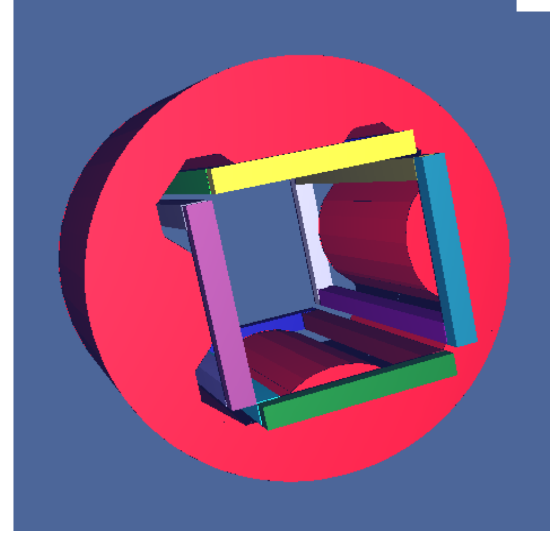


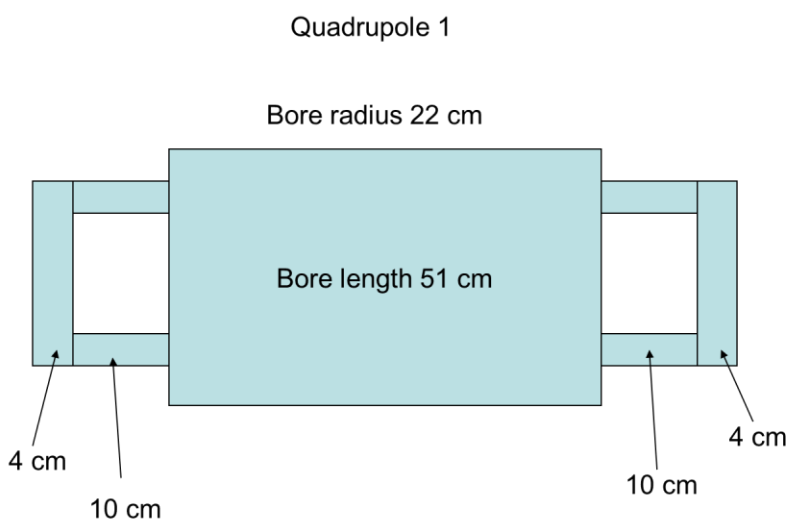
Geometry for Magnets

- Models for PHITS calculations for possible 2nd beam dump operation

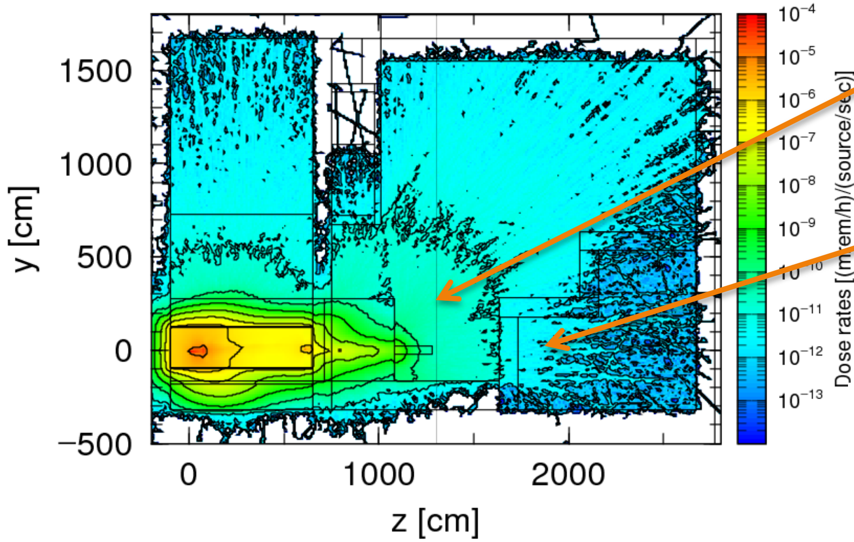








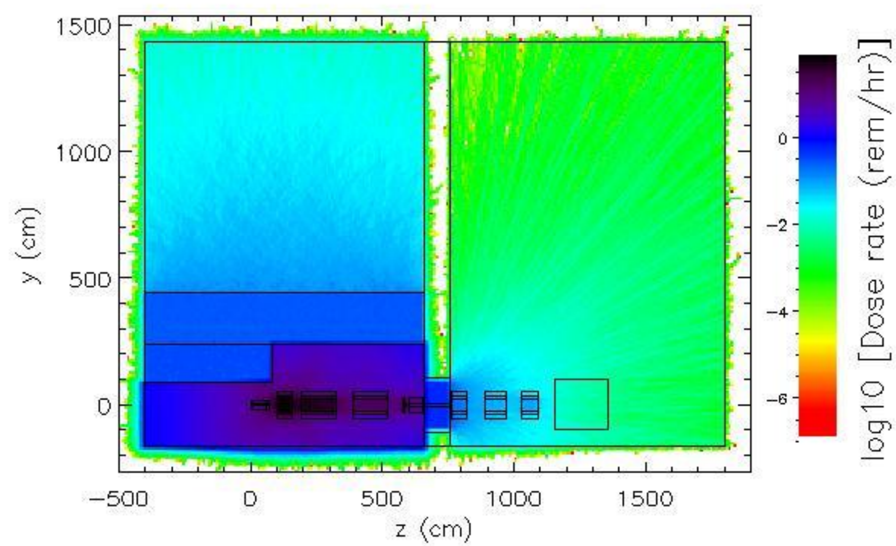
Shielding in Vertical Preseparator Region
Sufficient for 2nd Beam Dump Implementation (Worst Case)



Concrete bunker around quad triplet reduces prompt dose rate to < 100 mrem/h

Space behind concrete support filled with soil - within building: Activated soil is contained

Sources: ^{86}Kr beams, 233 MeV/u located at possible second beam dump, fragment catcher, collimator, wedge system

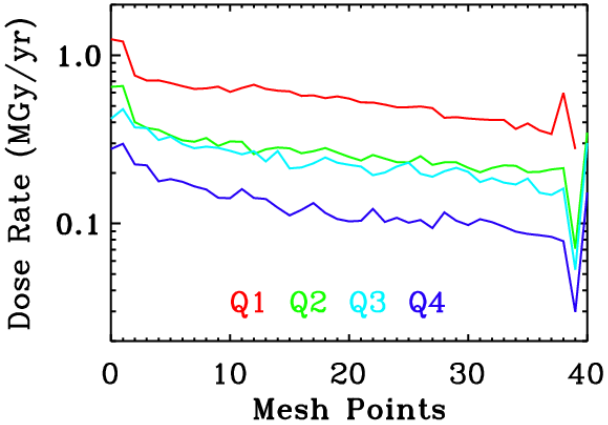


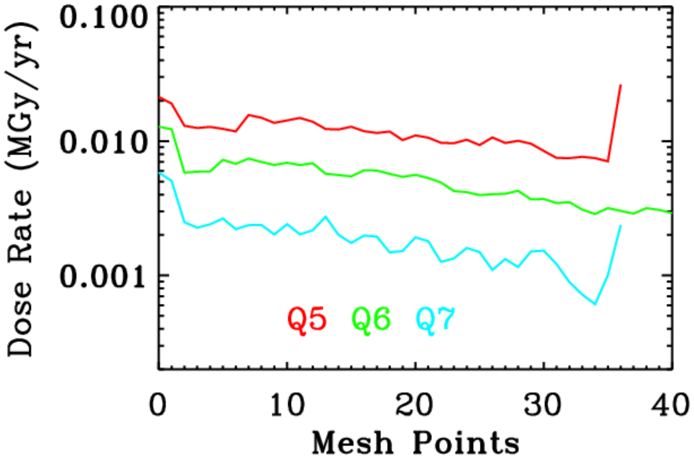
Residual photon dose rates after 4 hr

Hands-on access possible in vertical separator region

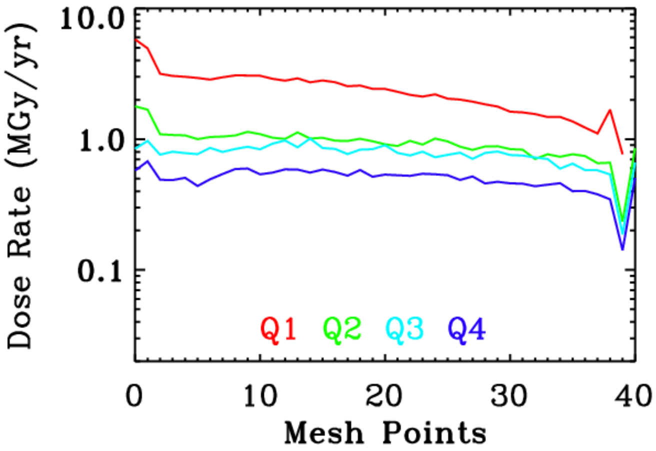
Radially Averaged Dose Rates To Quadrupoles

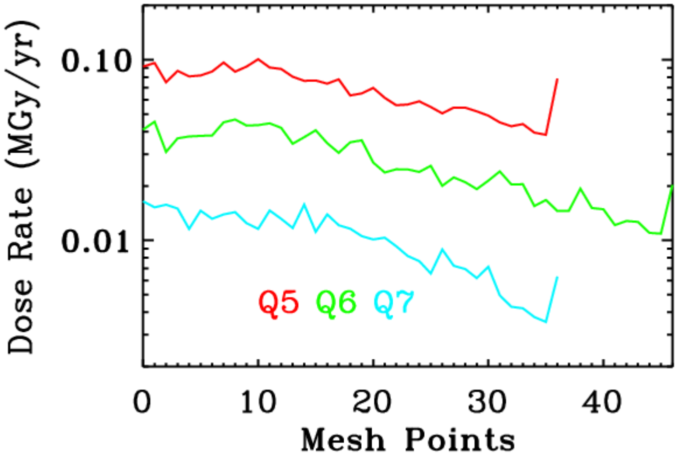
Model coils contain NbTi(75%)+Cu(25%)



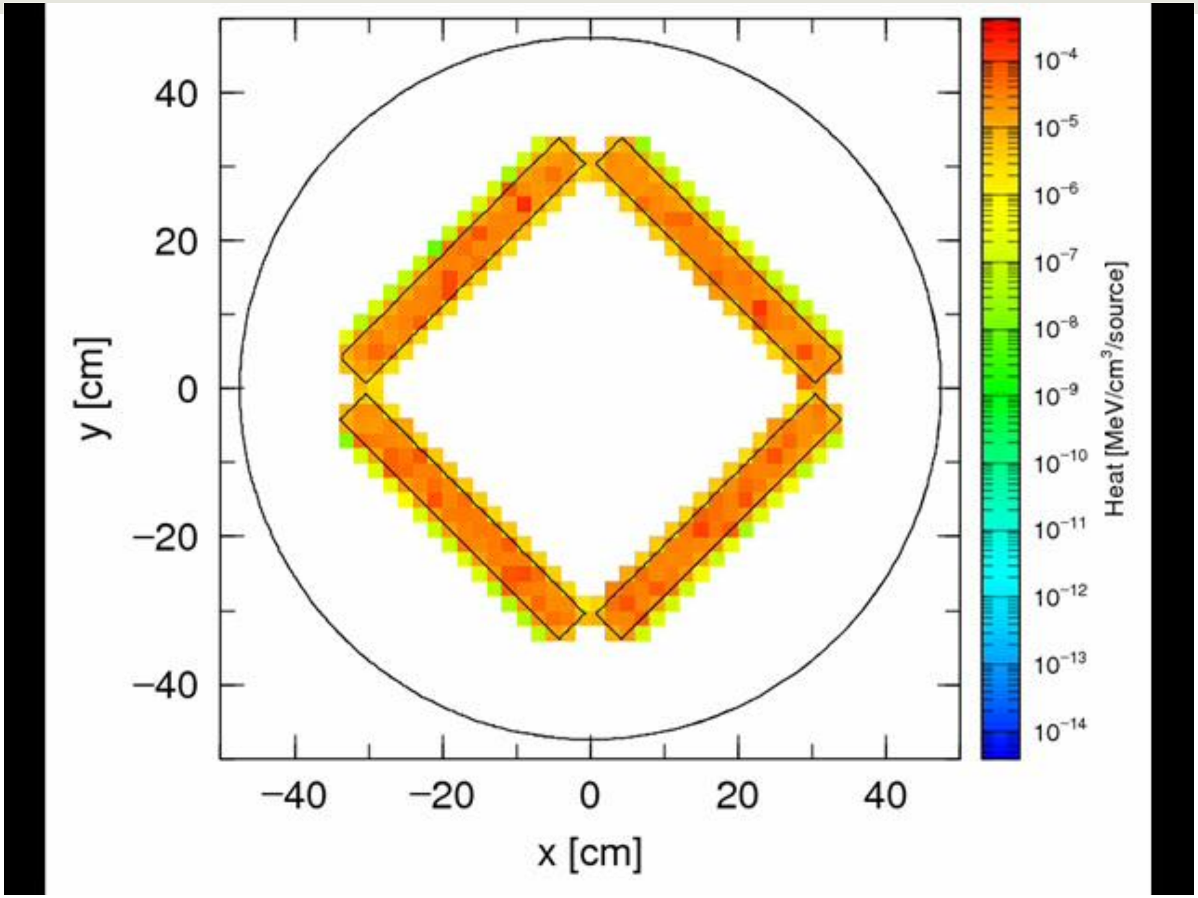


Model coils contain Stycast





Radiation Heating in Magnets
Example: Heating, Quadrupole Cross-section



2D IDL frames of PHITS heat mesh tally into Windows Movie Maker

$\Delta x = \Delta z = 1$ cm; $\Delta y = 1$ cm

Radiation Heating in Magnet Yokes, Coils

Supports Magnet and Non-conventional Utility Design

^{86}Kr, 233 MeV/u, at 300 kW

Magnets	Yoke Heating [W]
Q_D1137	52
Q_D1147	22
Q_D1158	11
Q_D1170	9
Q_D1195	3
Q_D1207	4
Q_D1218	2

Magnets	Coil Dose Rate [MGy/y]	Lifetime [y]
Q_D1137	2.54	10
Q_D1147	0.87	29
Q_D1158	0.80	32
Q_D1170	0.56	44
Q_D1195	0.14	182
Q_D1207	0.05	497
Q_D1218	0.04	673

Summary

- FRIB radiation environment is challenging
  - Power
  - Wide range of beams, beam trajectories
  - Shield studies are important
- SC technology will work